MONOLITHIC FREQUENCY FILTER DESIGNS
BASED ON A SAMPLED-DATA ANALOGUE
WAVE FILTER APPROACH

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UNIVERSITY OF EDINBURGH. JULY 1981.

ABSTRACT OF THESIS (Regulation 6.9)

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Address

Degree ...,....Ph.D.... Date .....23...July...1981....

Title of Thesis .....MONOLITHIC FREQUENCY FILTER DESIGNS BASED ON A SAMPLED-DATA ANALOGUE..WAVE...FILTER...APPROACH..

Frequency filters are widely used in communications systems today. Historically they have been constructed from inductors, capacitors and resistors and such circuits are well understood. However they suffer from the disadvantages of large physical size and high cost.

A monolithic realisation of frequency filters would greatly reduce the cost of systems in which filters are used and would increase their reliability in hostile environments.

In this thesis a novel approach to the realisation of sampled-data monolithic frequency filters is presented. The method is based on the use of sampled analogue signals and is related to the wave digital filter in its design techniques. The eventual monolithic realisation in NMOS technology is in the form of a switched-capacitor structure.

While the main body of the research is concerned with the implementation of filters which are based on distributed prototype networks, some work on integratable filters which are based on lumped element prototypes is also presented. For either type the design model is exact and the resulting filter is optimally insensitive to parameter variations. The filters are implemented using a technique which ensures that performance is limited by capacitor ratios, which are moderate as compared with alternative published approaches.

A prototype integrated circuit suitable for use in the audio frequency band has been designed to demonstrate the validity of the approach for the filters based on distributed prototypes and contains. filters of third, fifth and seventh order. Results are presented for these filters and also for a pseudo-bandpass filter which uses the periodicity of the prototype distributed network. The seventh order filter had a cut-off frequency of one eighth of the filter sample rate and achieved a stop band attenuation of well over 70dB

An implemetation of a wave filter based on a lumped element prototype is also described and results are presented. This work is expected to form the basis of a novel implemetation of bandpass filters.

The responses achieved for all the wave filters constructed show excellent agreement with the theory.

*Use this side **only***

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2. DECLARATION OF ORIGINALITY.

This thesis, composed entirely by myself, reports work conducted in the Department of Electrical Engineering at the University of Edinburgh exclusively by myself.

signed

M Reekie

H. M. Reekie

date: 20 July 1981.

3. ACKNOWLEDGEMENTS.

The author would like to acknowledge with grateful thanks the help and encouragement given to him by his supervisor, Prof. J. Mavor.

Thanks are also due to many friends in the Electrical Engineering Department and the Wolfson Microelectronics Institute. In particular the help of Dr. P. E. Denyer has been invaluable in the course of this work.

The authors research was financially supported by the Science Research Council, to whom thanks are also extended.

Finally thanks are due to my family and my fiancée, Christa, for their patience and support over the last three years.

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To Christa

1. INTRODUCTION.

Electrical filters which meet ever more demanding specifications are required today for instrumentation systems and the communications market. This leads to the filter designer requiring many more choices of filter technology then were previously available. It is the objective of this thesis to pursue the possibility of realising such filters in a single integrated circuit which can be produced on a high volume process in silicon technology. This should lead to complex integrated filter structures which can be produced in compact form at low cost, although the passivity of existing structures may be sacrificed.

In this thesis, a novel approach to frequency filtering, based on the so-called "wave filter", is advocated. In this work a "frequency filter" will be defined as “a transducer for separating waves on the basis of their frequencies" [i]. Designs for low-pass and band-pass filters in integrated form are presented in this thesis and results are given for several prototypes.

1.1 PASSIVE FILTERS.

The method of construction and the components used to make a filter depend on its frequency of operation [2]. At microwave frequencies resonant cavities are appropriate; whilst piezoelectric crystal units are very useful in the frequency range 5 to 150MHz, though the characteristics of the latter tend to be restricted to band pass and notch filters. Ceramic filters, though less selective, are possible choices for the intermediate frequency stages of a radio receiver. Mechanical filters are also of use for the lower frequency stages of a circuit. However, in the frequency range 5 to 200kHz the dominant type of filter has been comprised of lumped capacitors and inductors, together with resistors. These circuits are known as RLC filters [3, 4].

RLC filters have been extensively studied and their design has been greatly eased by the publication of many sets of tables of element values, see for example those in [3]. In fact, the principal advantage of the RLC filter is the ease with which it can be synthesised, though the advantages of passiveness and zero power consumption are very important.

The RLC filter, because it is passive, cannot become unstable [5] and a particular class of RLC filter, the resistively terminated ladder filter shown in Fig. 1.1 is also maximally insensitive to variations in it5 element values [6].

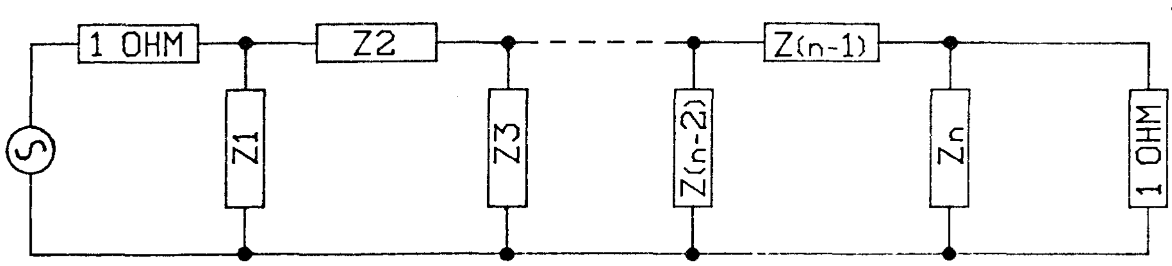

Figure 1-1: Resistively terminated ladder structure.

This insensitivity is due to the fact that a RLC ladder filter can permit maximum power transfer between its source impedance and its load impedance within its passband. At these points of maximum power transmission the partial derivitive of the power transfer function with respect to any of the element values must be zero, since to have more than maximum power transfer is impossible in a passive system. These factors give the ladder filter all the electrical advantages that could be desired and explain the popularity of this class of filter over many years. The disadvantages of these filters, however, are becoming more important in the age of micro-electronics, where miniaturised filters are potentially possible in integrated circuit form. The minimum physical sizes of the capacitors and, more particularly, the inductors required by an RLC filter are strictly limited by their electrical values and since these values are often quite large the resulting components are often also large, particularly for low frequency applications. This results in a filter system which is bulky and incompatible with modern integrated systems.

The second disadvantage of the ladder filter is that its. components must be trimmed to their correct values. This is a long and time consuming iterative process which must be carried out by trained personnel on a complex, expensive, machine. This trimming operation is often the most significant part of the total cost of the filter.

The third disadvantage of the RLC filter is that it is not electrically programmable and therefore its Characteristics are fixed at the time of its manufacture. While this is not a serious disadvantage in some applications it makes the use of these filters impractical in others.

The last major disadvantage of the RLC class of filters is that they are cannot be quickly multiplexed within a circuit. Multiplexing is a circuit technique in which a single complex circuit element is switched rapidly between different parts of a network to fulfil the function of several elements. This leads to the circuit having the advantages that would be gained by having several of the complex elements without incurring penalties of extra components and power consumption. If multiplexing had been possible the size of the filter could have been less important compared to its usefulness in the circuit.

Thus in spite of their attractive features, these disadvantages have caused circuit designers to look for designs which are smaller and more easily constructed while trying to retain the desirable characteristics of the RLC class of filters.

1.2 EARLY ELECTRONIC FILTERS.

A method used in the early 1950's to reduce the size of RLC filters was to replace the inductors by some active elements *[7]*. This was desirable because the unavoidably large size of the inductors required for low frequency conventional RLC filters resulted in a bulky filter system. Inductors also show poor reliability when subjected to vibration or other severe environments. Replacement of the inductors by a set of active components created a new class of circuit, the RC active filter, which depended on the use of differential amplifiers for its operation. Early circuits were made using thermionic valves and were clearly not practical by modern standards, though they demonstrated that the method was feasible. Not until the late 1940's, after the invention of the transistor family, did the concept of semiconductor differential, amplifiers at a reduced size and cost become feasible, though large scale production of the new devices did not occur till the late 1950's. Even then problems caused by the use of discrete components held back the widespread use of RC active filters, and it was not until the production of cheap monolithic operational amplifiers in the 1960's that substantial use was made of this type of circuit. The high volume of commercial sales was such that in 1977 the active filter market in the USA was in excess of 15 million dollars *[8].* However, RC active filters suffered from problems of instability [8], and tended to have responses that were sensitive to variations in the component values of the filter. Also, while the size of the circuit was greatly reduced, it was still large compared to other parts of an integrated circuit based system.

These limitations caused the search for further filter circuits to continue, with the aim of building a complete filter on one integrated circuit. This would give the filter increased reliability and reduced cost and size.

The development of transistors and digital integrated circuits made the digital computer practical in the early 1960's, and one of the uses to which it was put was simulating active filters. This required the continuous voltages and currents in the active filter to be sampled, and the samples to be represented by digital numbers. The initial programs did not run in real-time but could analyse and predict the behaviour of an analogue circuit. As computers became faster and more widely available, real-time signal processing became possible. This required the development of a whole new branch of signal processing theory based on sampled-data filters and this theory, and the circuits evolving from it, will be discussed in the next chapter.

1.3 LAYOUT OF THESIS.

The aim of this work has been to produce a prototype integrated frequency filter with a specified amplitude response. In chapter two the variety of techniques available to achieve this end are briefly discussed and the concept of the wave filter is introduced.

In chapter three the theory of wave filters is developed, with consideration being given to the circuit elements and their interconection.

In chapter four the computer simulation program developed as part of this work is described. This program will synthesise, simulate and present graphical results for distributed and lumped element filters.

Chapter five describes the method chosen for the implementation of wave filters which are based on a cascaded transmission line network. Also discussed in this chapter are the problems present in the method chosen and their effects on the filter response. Two filters that were built from discrete components are described and results presented.

The three-port adaptors which are required to produce wave structures which model lumped element filters are described in chapter six. A discrete component third order band-pass filter which gives cutoff frequencies accurate to better than 1% and a stopband attenuation of greater than 80dB, is described and the full results obtained from it are presented.

Chapter seven is devoted to the design of the integrated circuit which was produced as a major part of this work. It contained three frequency filters, all with designed passband ripples of 0.2dB. The seventh order filter achieved a stop band rejection of better than 70dB. Process dependent details and the integrated circuit layouts used are given.

The results obtained from the integrated circuit described in chapter seven, together with a comparison with the theoretical results, are given in chapter eight.

Chapter nine contains a discussion of wave filters in general and presents the authors conclusions regarding the potential of sampled-data analogue realisations of these filters.